

Space weather: Impact on cascading power grid failures A simple model and illustration

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Scope of the project

- Assess the effect of space weather on linked elements of the power grid in different states (predicted peak in 2013)
- Analyze the effects of grid operator actions on cascading grid failures, and identify grid management policies (production reductions) that are globally optimal for the different grids (states) involved

CAVEATS

- We are aware of the Optimal Power Flow (OPF) but do not use it explicitly.
- System operators are crucial to the formulation of OPF problems, but System Operators do not seem to like probabilistic models.
- We do not consider the introduction of natural/renewable power mandated by government.
- We are aware of the industry accepted safety model called Security Constrained Optimal Power Flow (SCOPF), but to a large extent it does not seem to account for cascading effects.

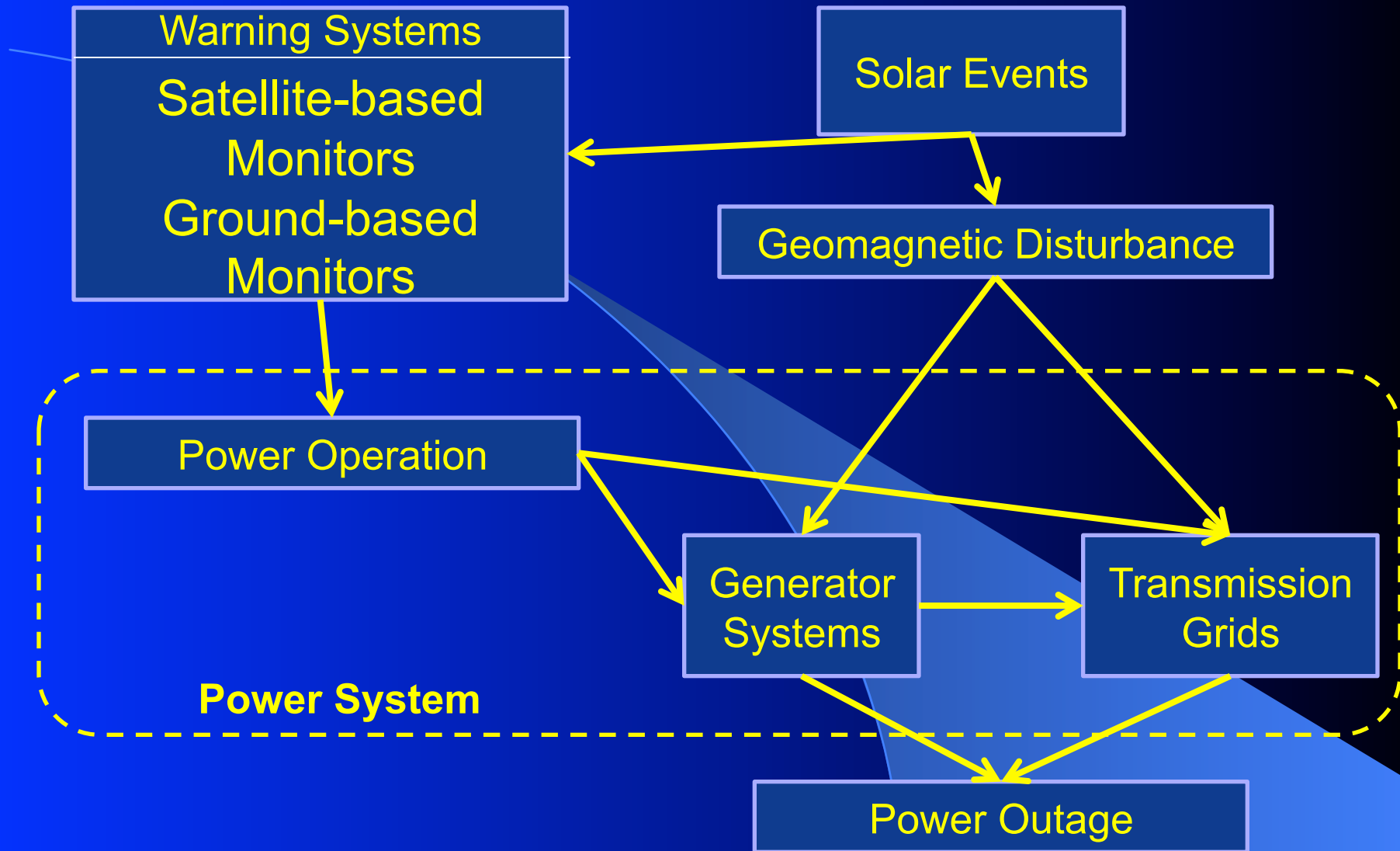
Our (simple) models involved: Loads, capacities and economics

- Solar activity forecast
- Effects of solar activity and geomagnetic storms (loads) in different locations
- Warning system (satellites and magnetometers)
- The power grid system: a simplified representation of linked state grids (WA, OR, and CA)

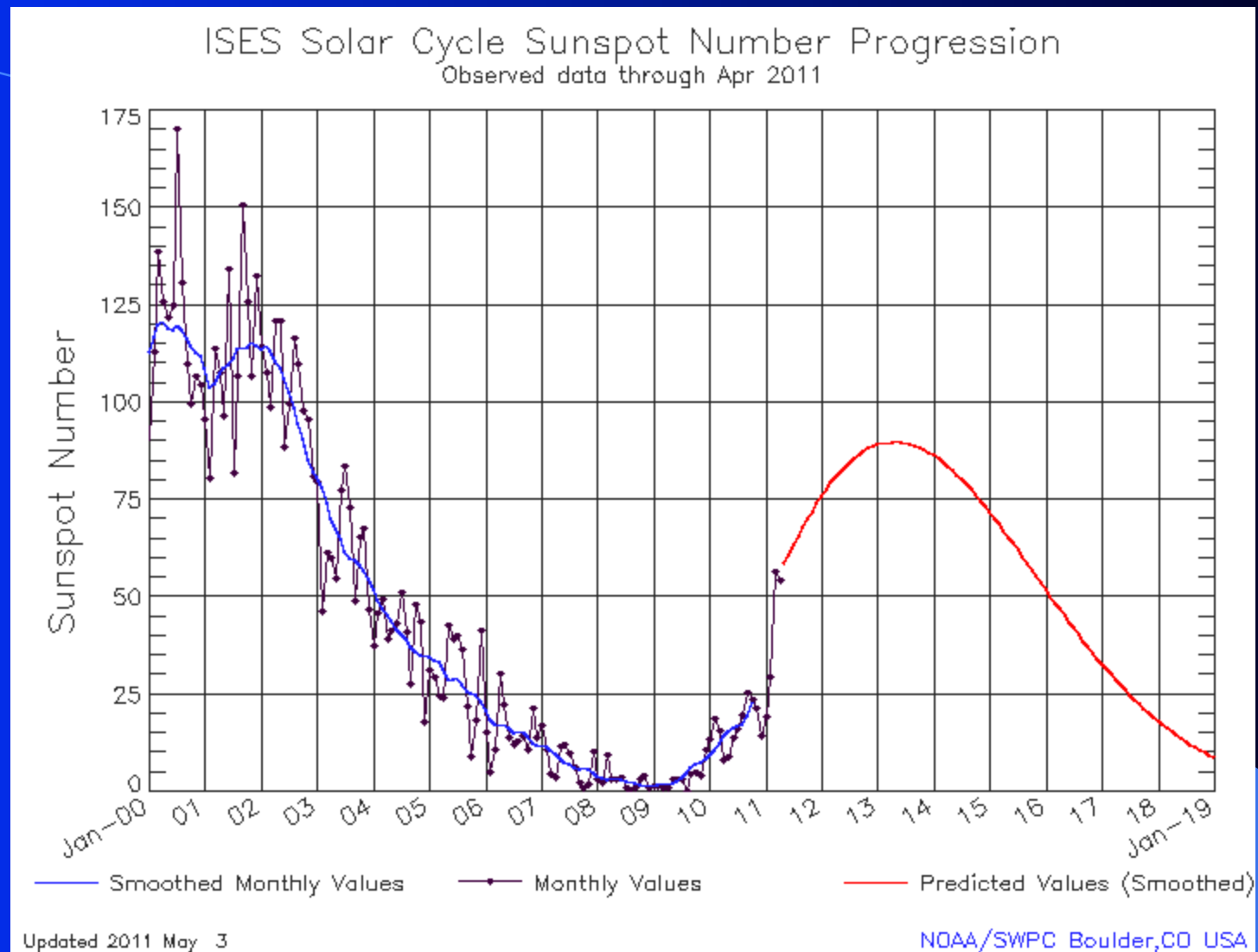
Models (cont.)

- A simple model of grid performance (failure risks) and cascading effects
- Economic (benefits) optimization for each state's grid and for the whole system
- Optimal policy for a set of US States with grid interactions and potential cascading failures

Problem Overview



Solar Activity Forecast. Source: NOAA

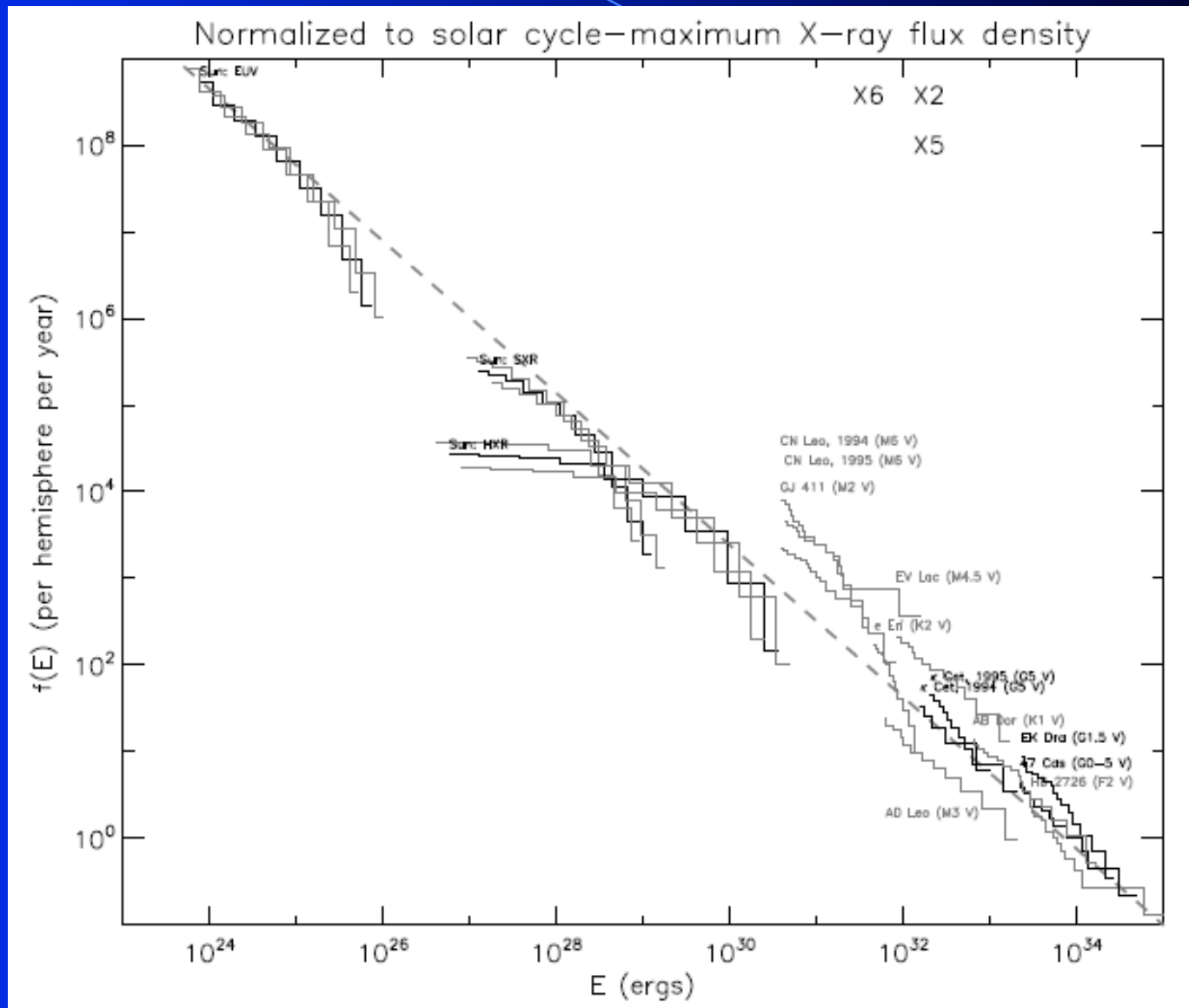


Warning systems: “Solar Shield Project” & SUNBURST

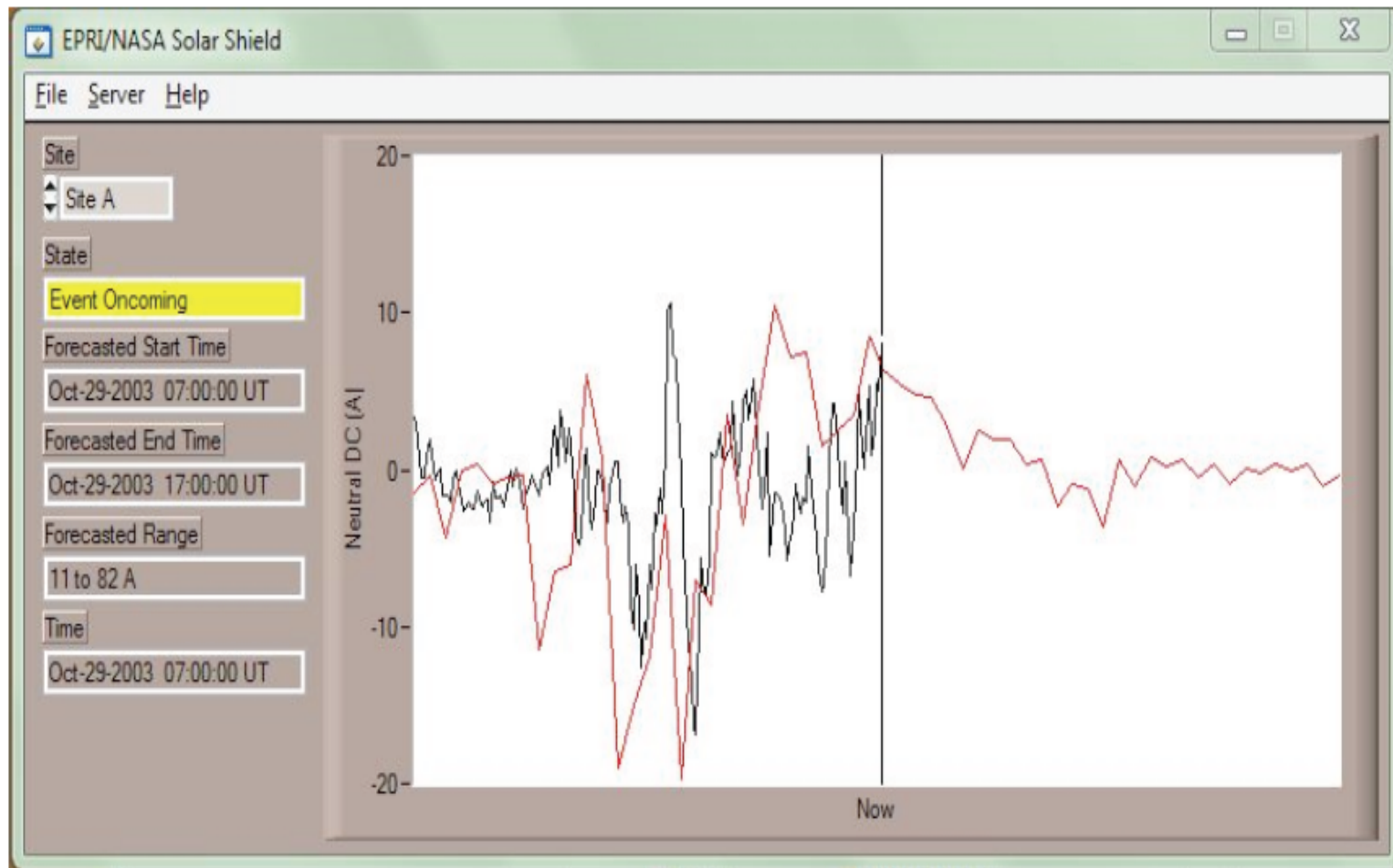
- “Solar Shield Project “ = Forecasting system for Geomagnetically Induced Currents (GIC)
 - By EPRI & NASA Goddard
 - Enhance SUNBURST: research tool used by US power industry
- Two forecast levels:
 - LEVEL 1: long lead time; 1-2 days. Based on remote solar observations and heliospheric magneto-hydrodynamic (MHD) simulations.
 - LEVEL 2: short lead time; 30-60 minutes. Based on in-situ L1 point solar wind observations and magnetospheric MHD simulations.

Loads: Flare Energy Frequency Distribution

Source: C.J. Schrijver, Lockheed Martin, 2010



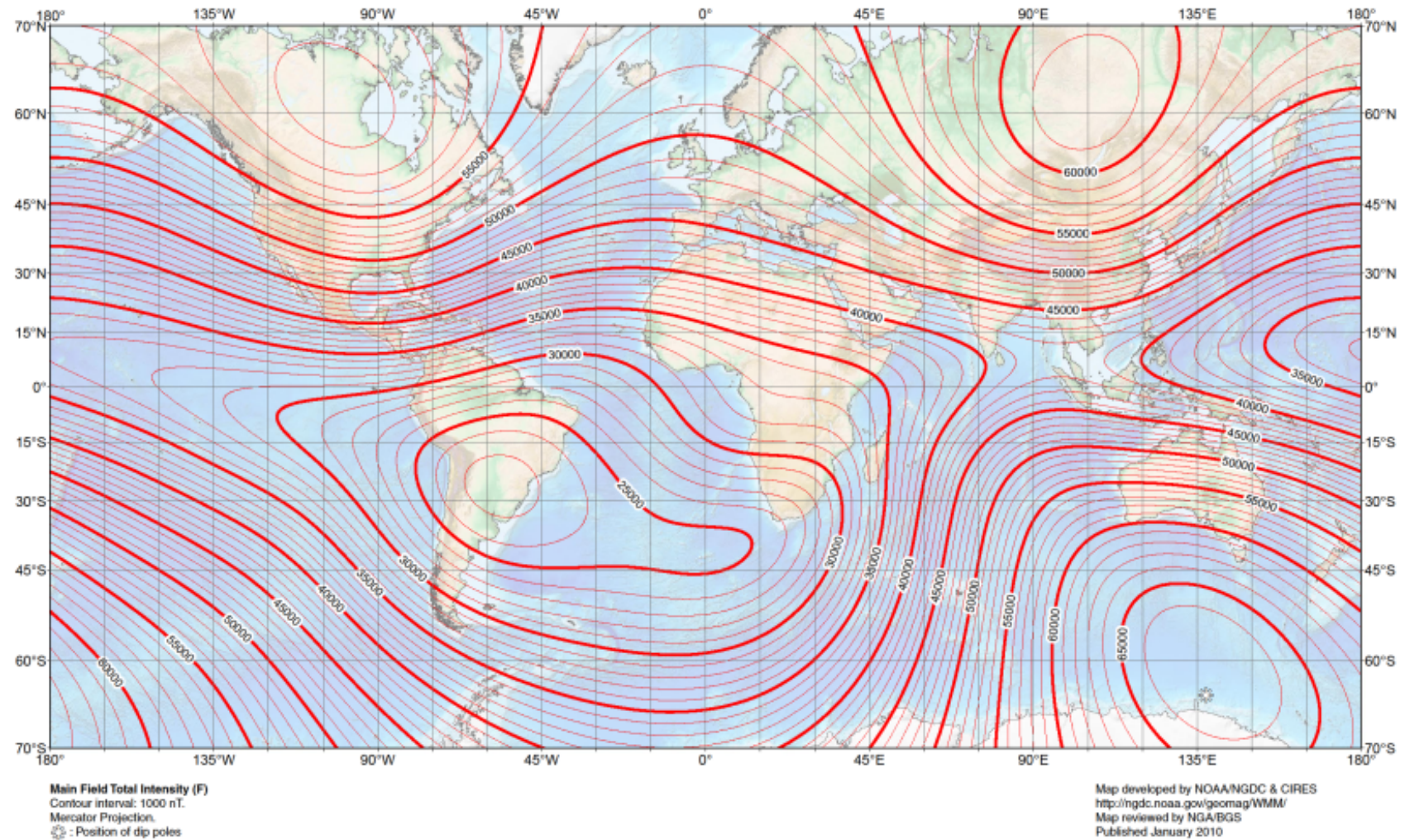
Solar Shield Grid Operator interface (warnings)



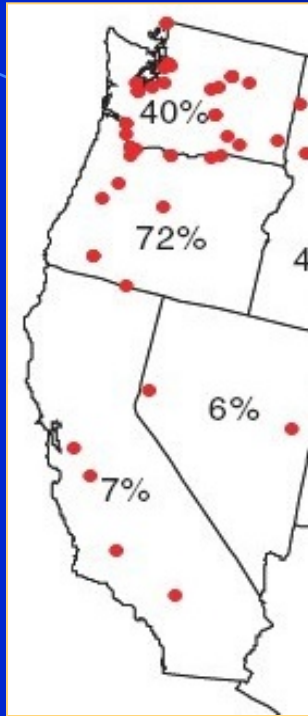
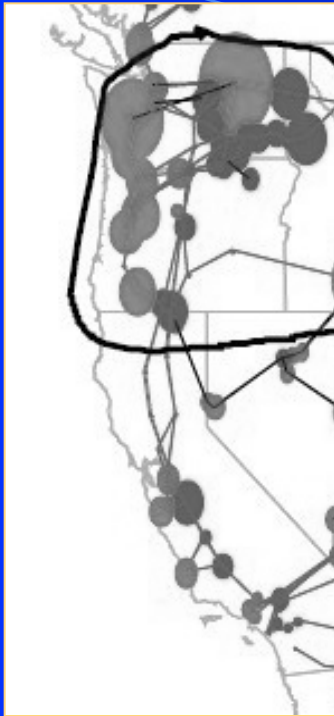
Left side: level 1 information so far. Right side: level 2 forecast

Effects of Solar Activity and Geomagnetic Storms

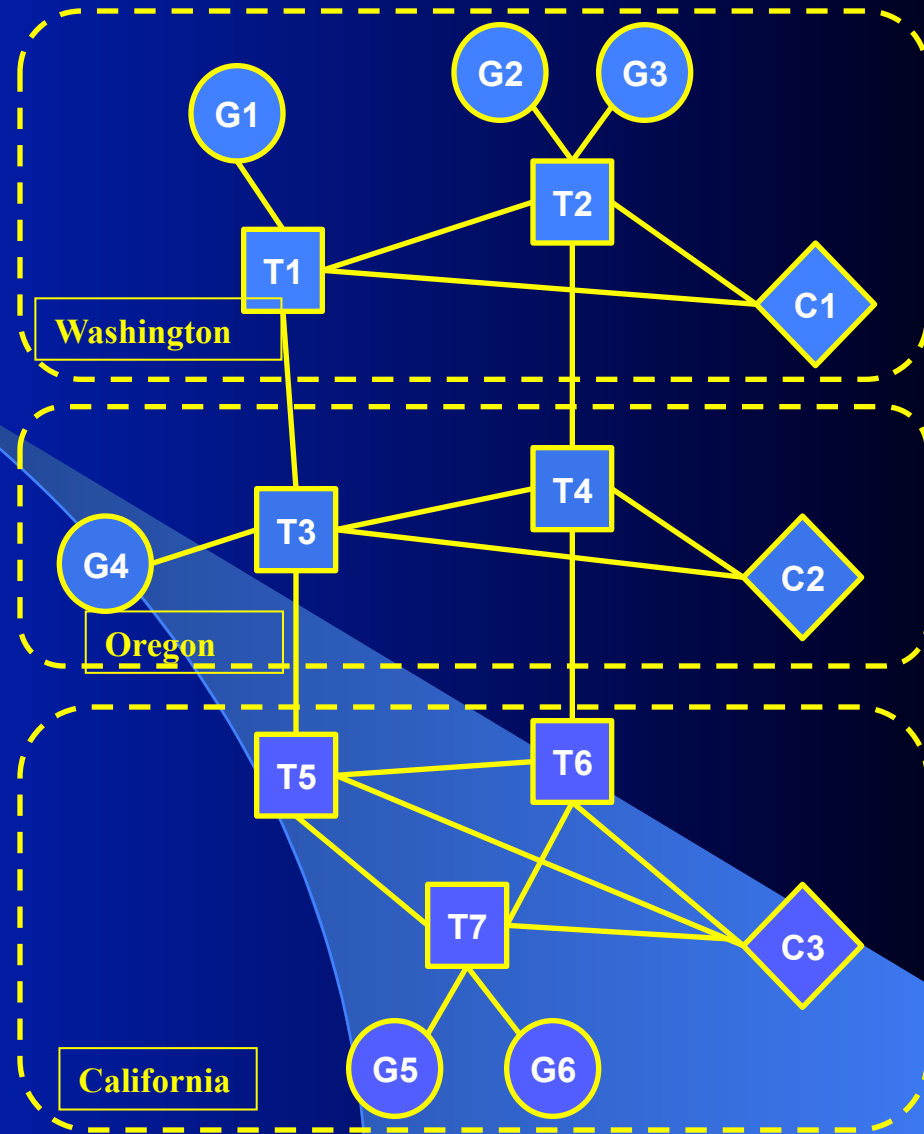
US/UK World Magnetic Model -- Epoch 2010.0
Main Field Total Intensity (F)



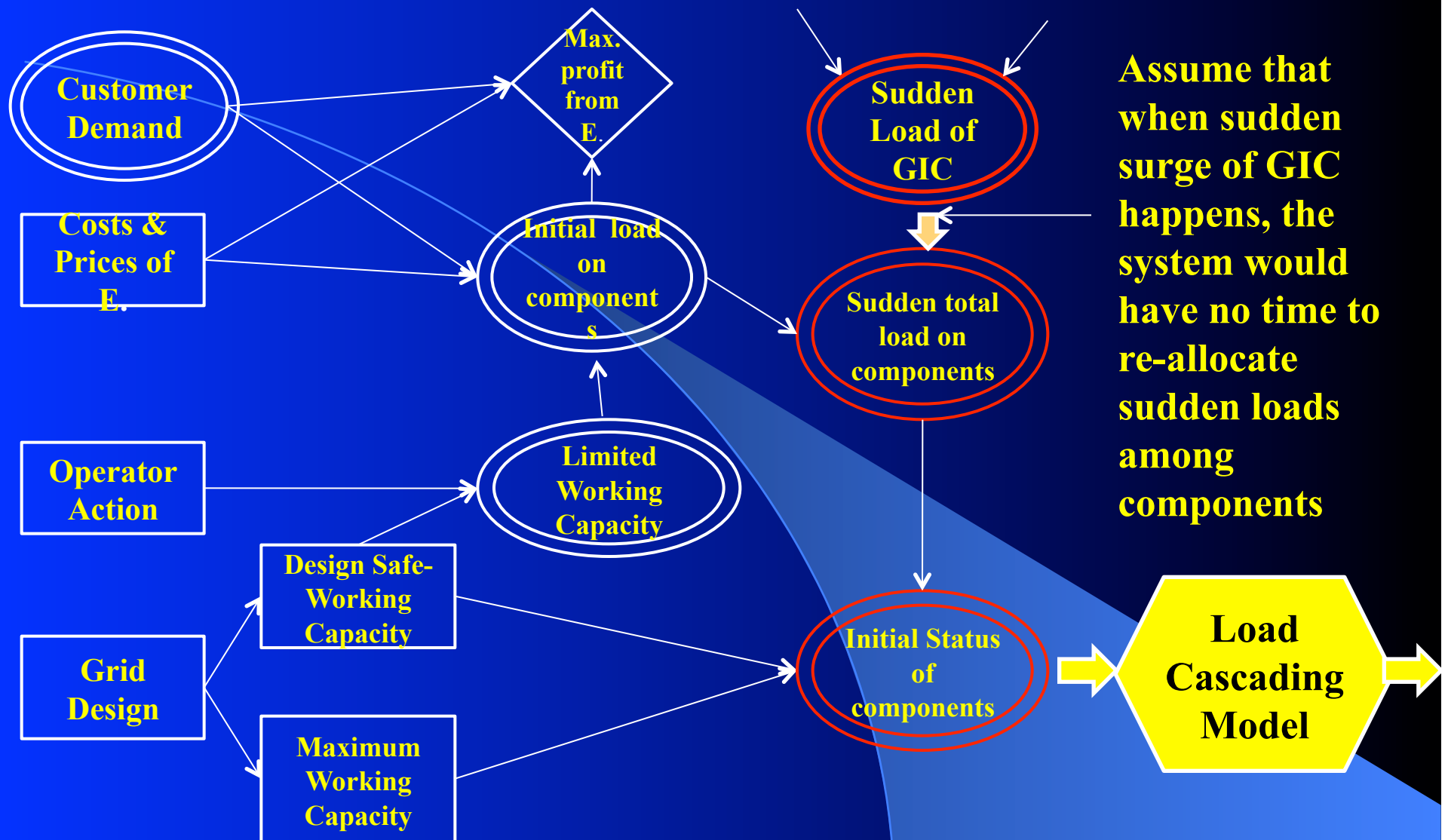
A simplified, schematic electric power grid



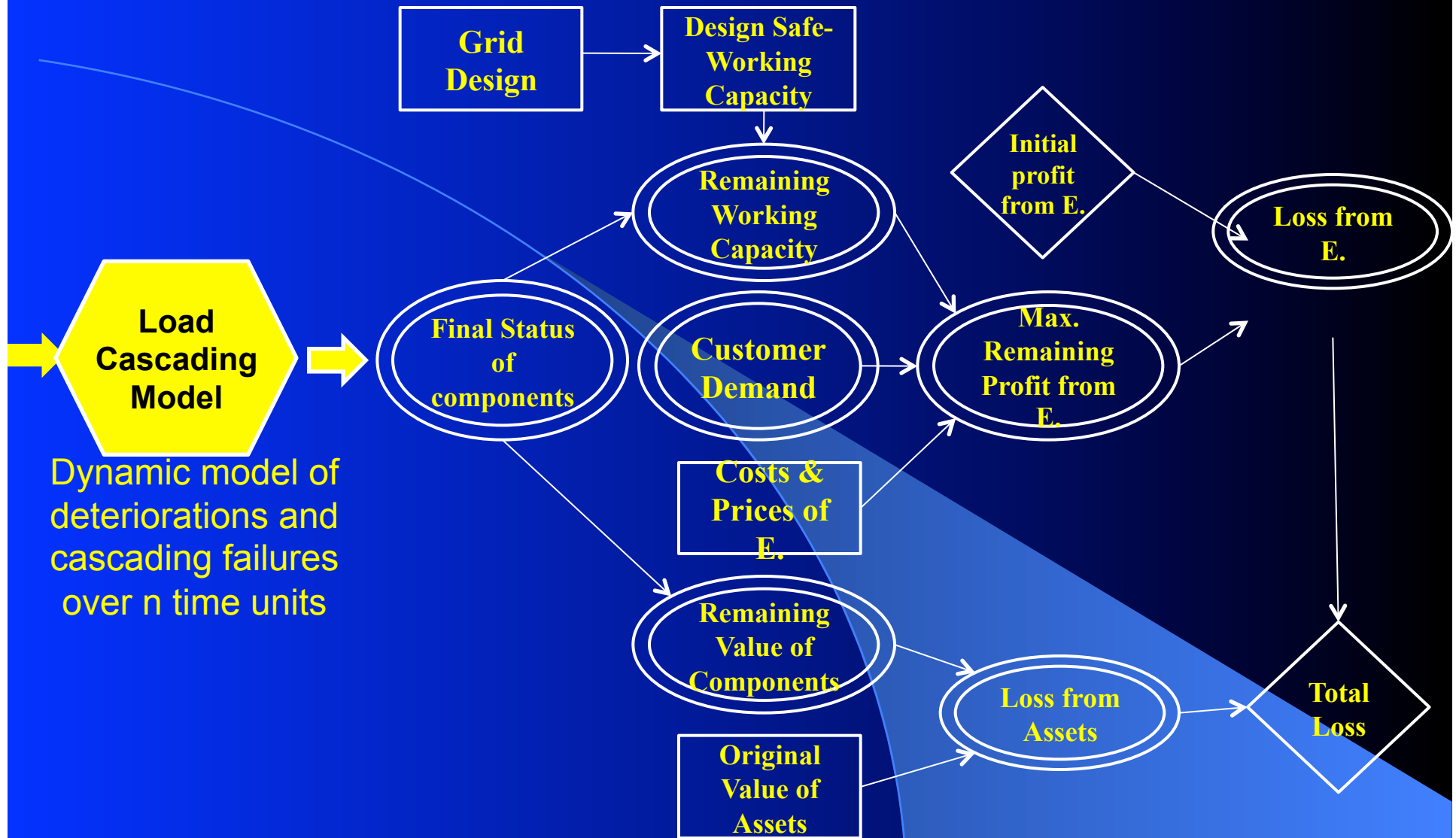
G: Generator
T: Transmission line
C: Consumer



Evolution of the Power Grid: initial state

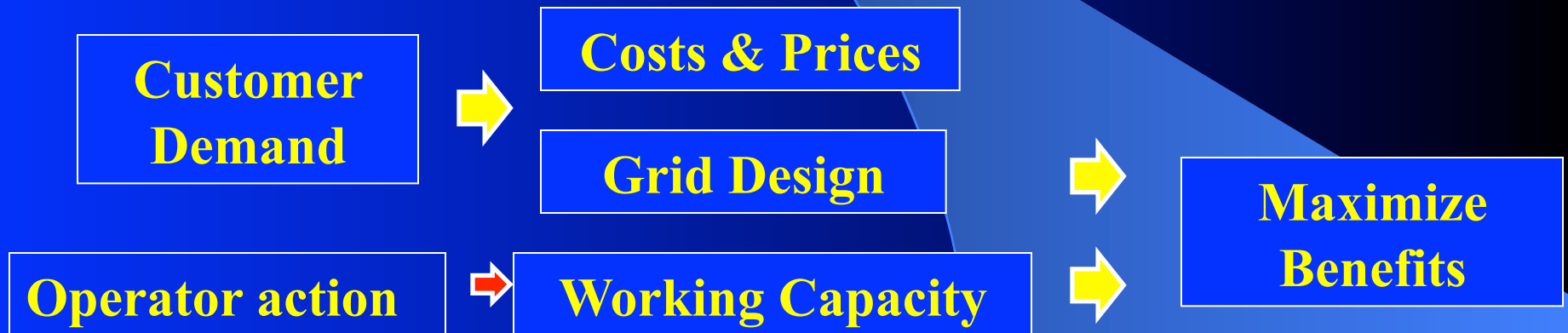
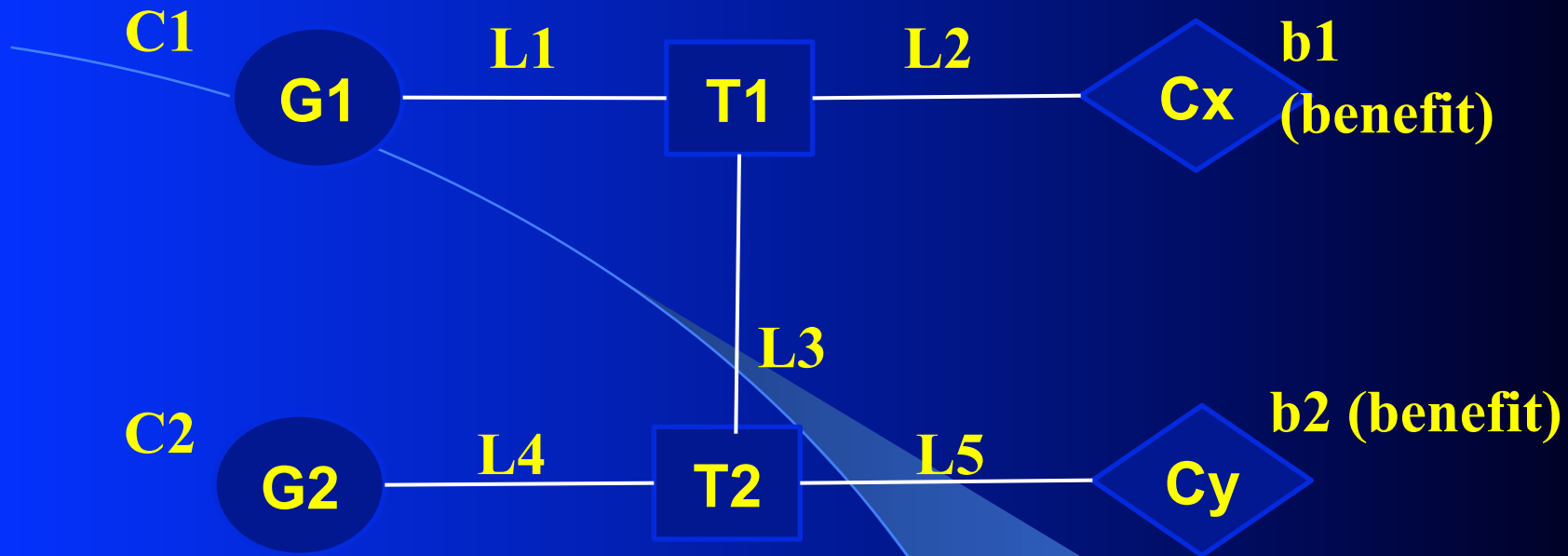


Final Status of Power Grid



Optimization Example

Consumers, generators, transformers, lines and benefits



Grid performance model

- Pre-event normal performance:
Electric path and distribution set so that
Pre-event load \leq Maximum capacity
(robustness)
- Failure under sudden GIC load:
Pre-event load + sudden GIC load
 $>$ Maximum capacity (robustness)
=> Component failures => cascading failures

Operation optimization

- Pre-event load distribution
 - Maximization of benefits:
pre-event load \leq design safe-working capacity
- Given a warning of a solar event (of magnitude K_p):
 - Operators lower capacity and re-rout flow
So that event load still \leq safe-working capacity

Cascading failures dynamics simulation

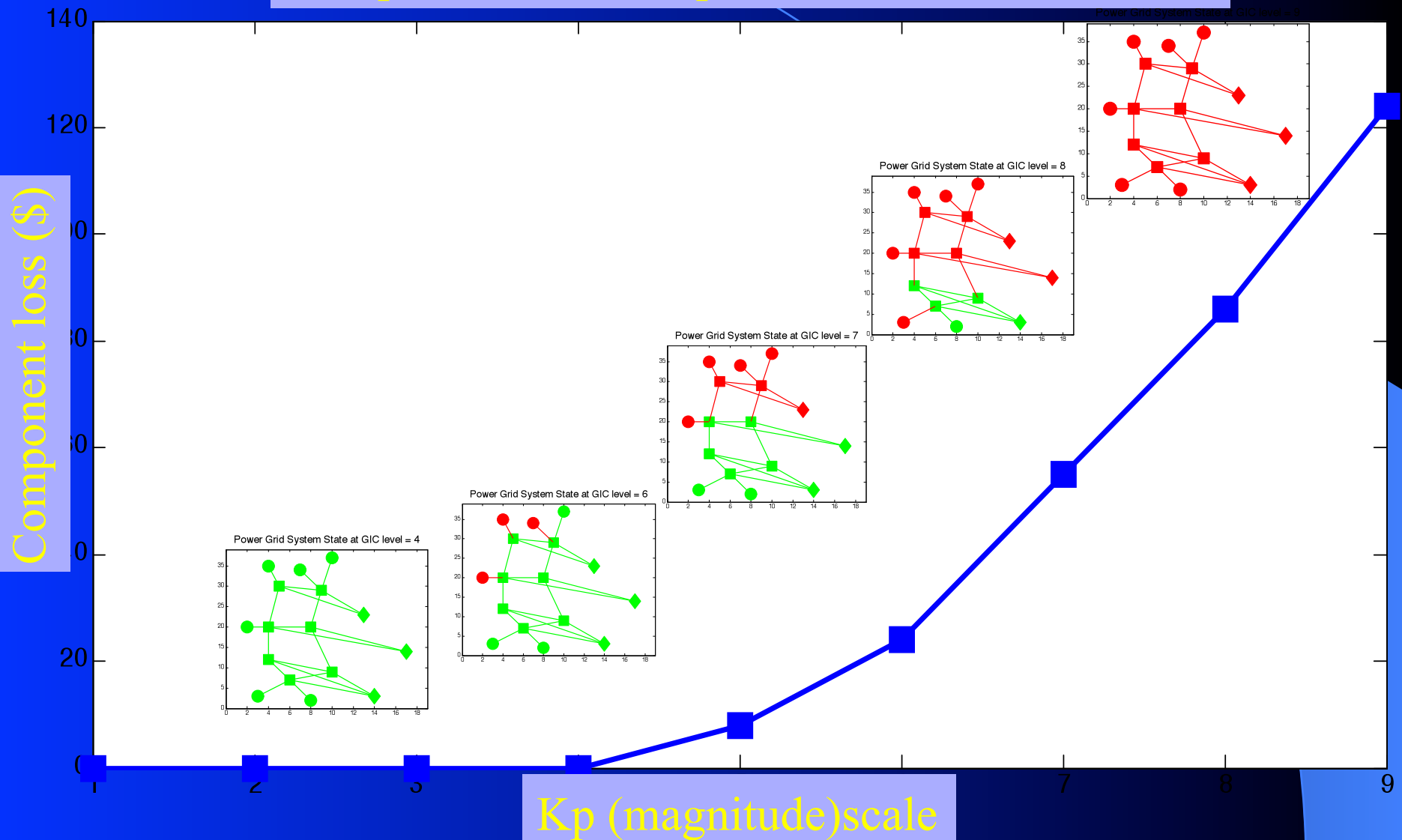
- A network model
 - Nodes: generators, transformers, customers (G, T, L, C)
 - Links: Gen->Lines; Transf->Lines; Cust->Lines
- States of G, T, L: good, medium or bad (failure)
- Assumption: the state of each node is influenced only by the state of its neighbors (linked components)
- Interactions: conditional probabilities of failure given the state of neighboring nodes
- Transition probabilities for each component based on state of the neighbors (simplification: the highest probability of degradation implied by neighbors' states)

Algorithm

- Initial state: result of operator action
- At each time and for each component
 - Define component's current state
 - Define its conditional probabilities of degradation given the state of linked components
 - Build the degradation probability matrix
 - Identify the highest transition probability => determines the component's new state (at the next time) with probability 1
- Next time: repeat the algorithm with components in new state.

Effect of solar event size on cascading failures

Component loss vs K_p when NO action is taken



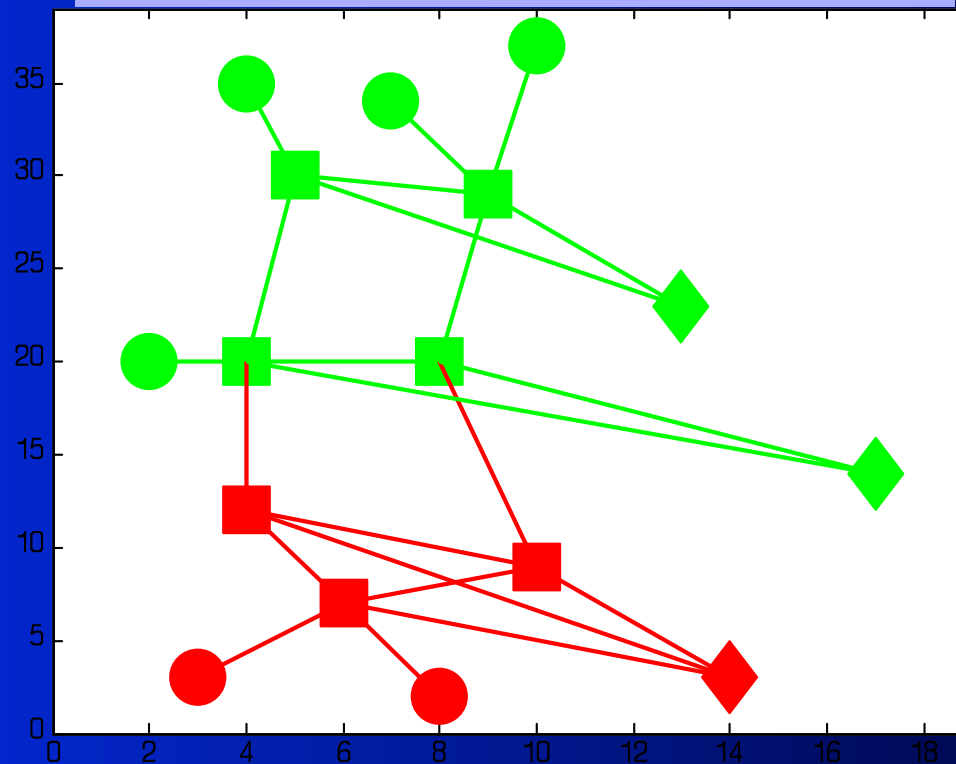
What happens when grid operators in the different areas take different actions?

Action= Reduction of production.

Extreme action: reduction by 50% [0.5, 0.5, 0.5] in all 3 States (WA, OR, CA)
given a predicted solar storm of magnitude 9

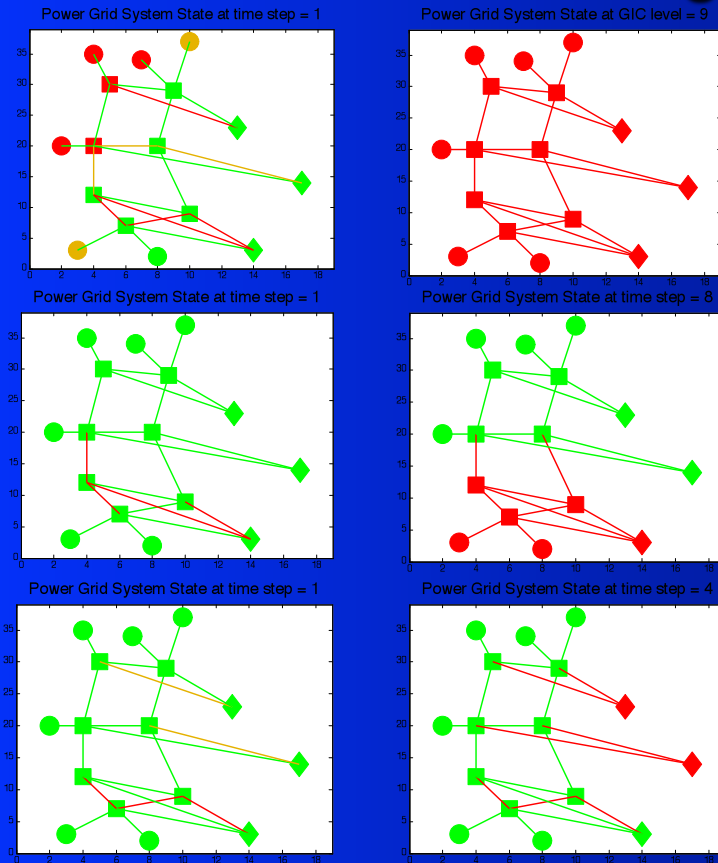
Power grid system state simulated from time 1 to time 8 (\Rightarrow state at time 8)

Power grid system at time 8



Comparing different actions

State of the grids in step 1 and step 9



No action (full production):
[1,1,1]

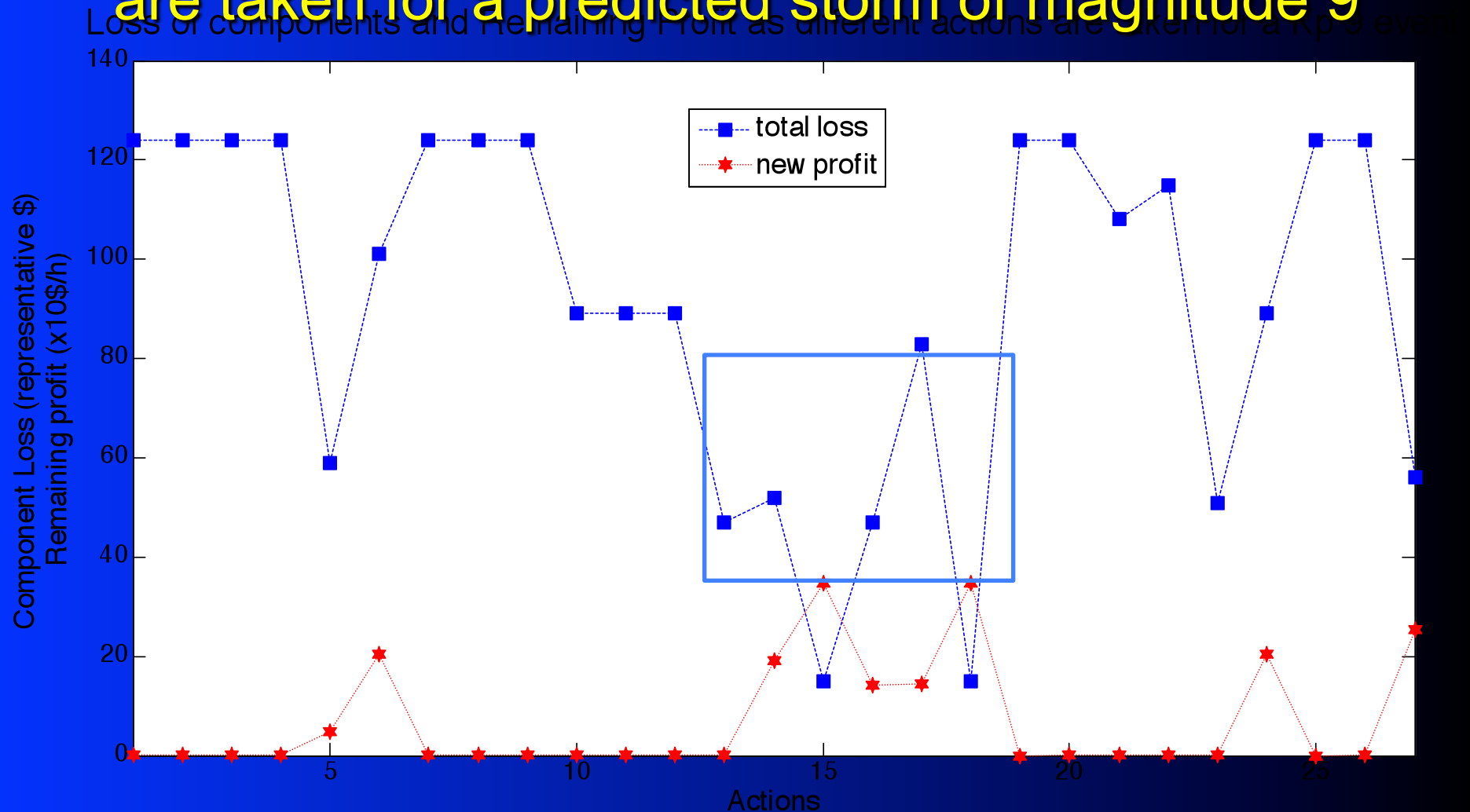
Extreme action: [.5 .5 .5] , all
grids react drastically (reduce
production by 50%)

Independent action, e.g.:
[.5, .7, 1] => production in WA
50%, OR 70%, CA 100%

Next question: What is the best action for each grid operator that minimizes component loss and maximizes benefits for entire grid?

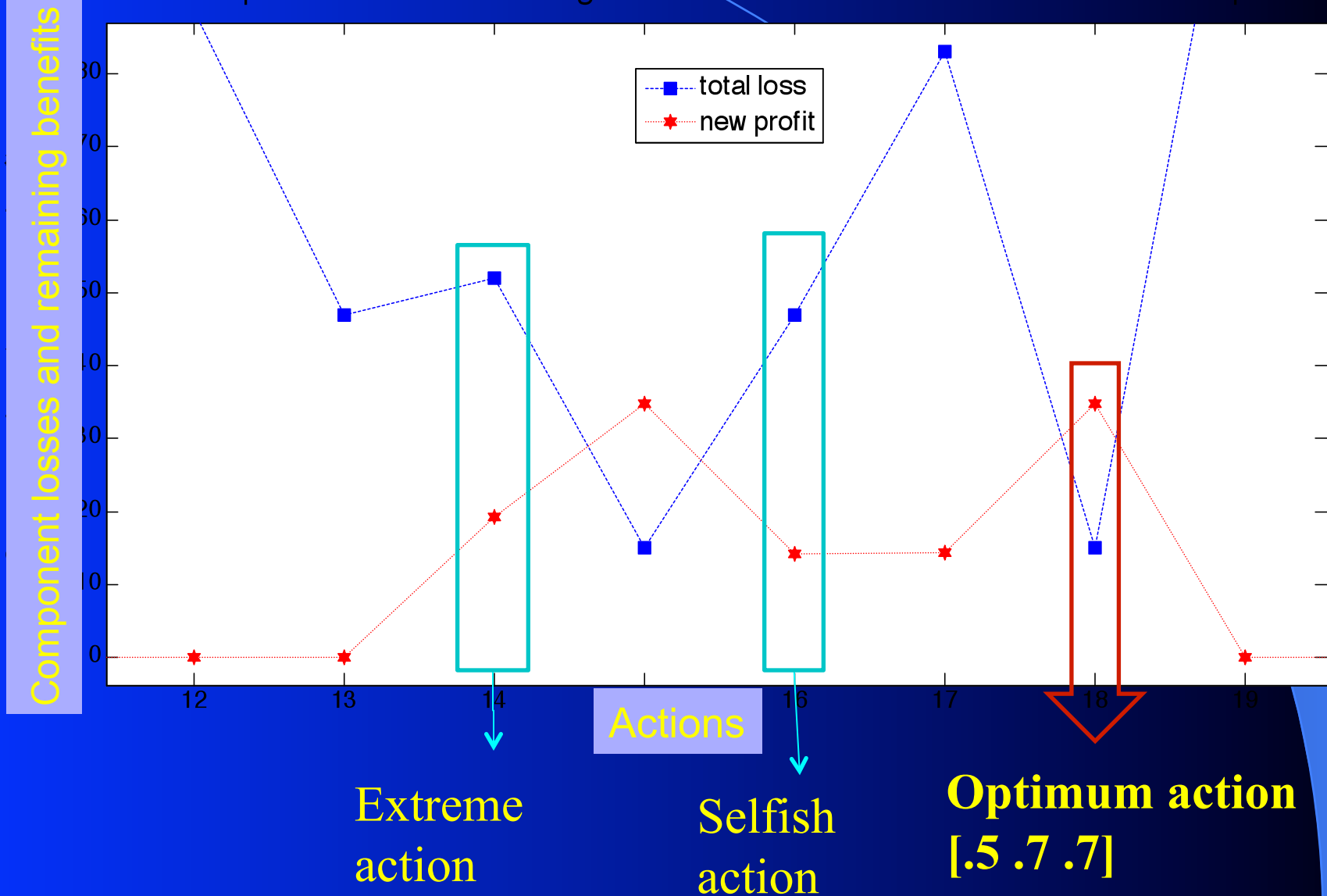
Effect of all possible actions:

x axis: loss of components and remaining benefits as different measures (y axis : production levels) are taken for a predicted storm of magnitude 9

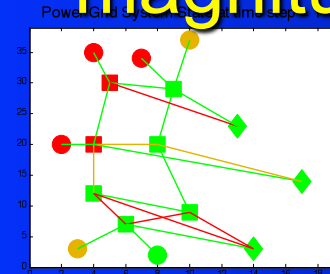


Optimum action at the global level for a predicted storm of magnitude 9

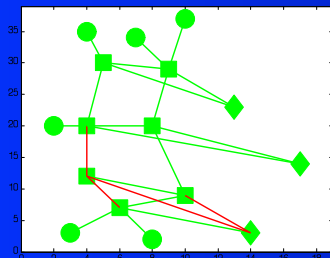
Loss of components and Remaining Profit as different actions are taken for a Kp 9 event



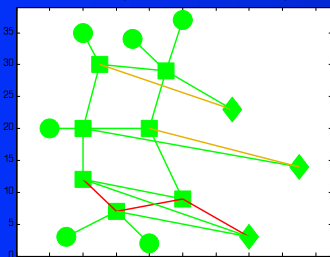
Comparing results (loss of grid in a storm of magnitude 9) for different actions by each State



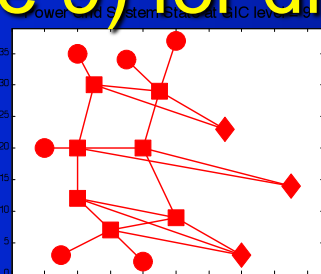
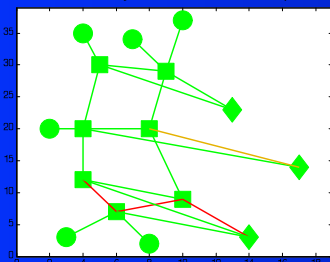
Power Grid System State at time step = 1



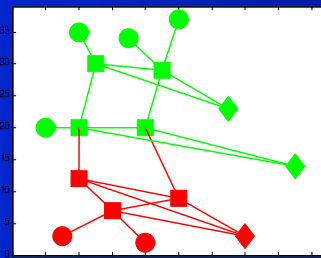
Power Grid System State at time step = 1



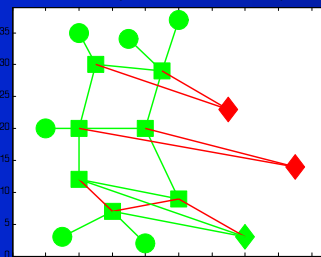
Power Grid System State at time step = 1



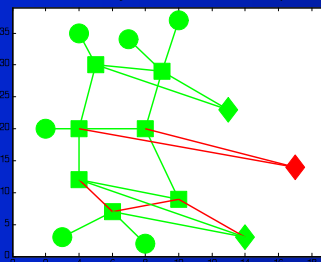
Power Grid System State at time step = 8



Power Grid System State at time step = 4



Power Grid System State at time step = 4



No action: [1,1,1]

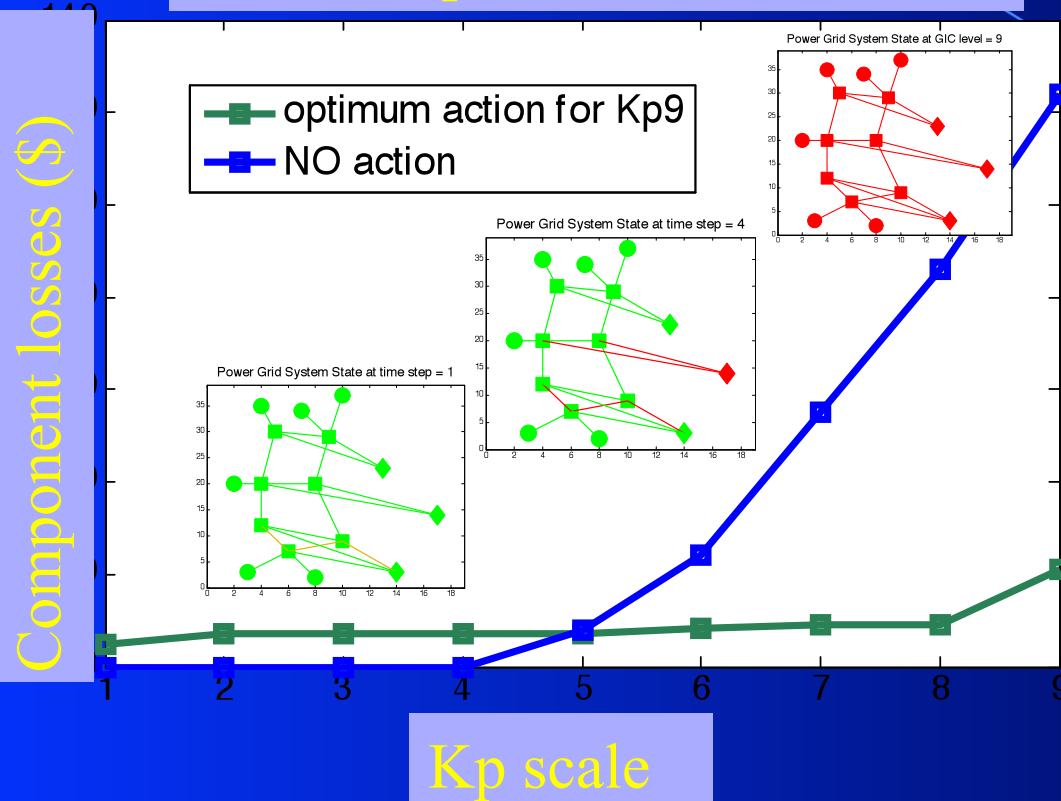
Extreme action: [.5 .5 .5] , all grids react drastically

Optimal independent (“selfish”) action: [.5 .7 1]

Optimum action (maximum benefits: [.5 .7 .7] =>Oregon and California need to coordinate

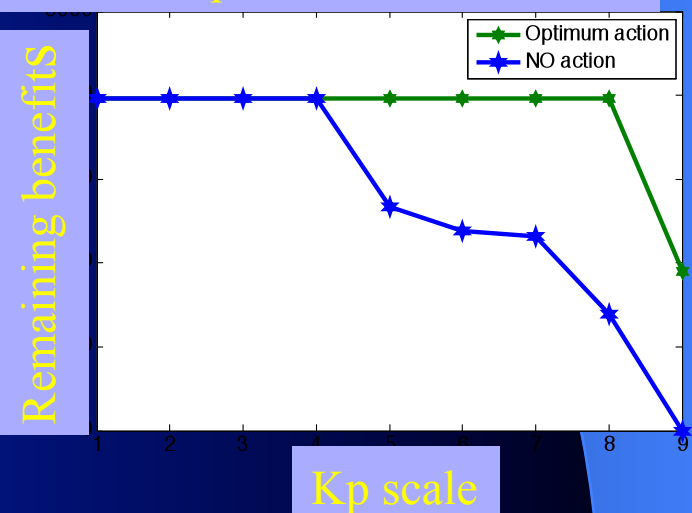
Effects of optimal action for a magnitude 9

Losses: Optimum vs No action



Component losses before Kp5 due to line overload.

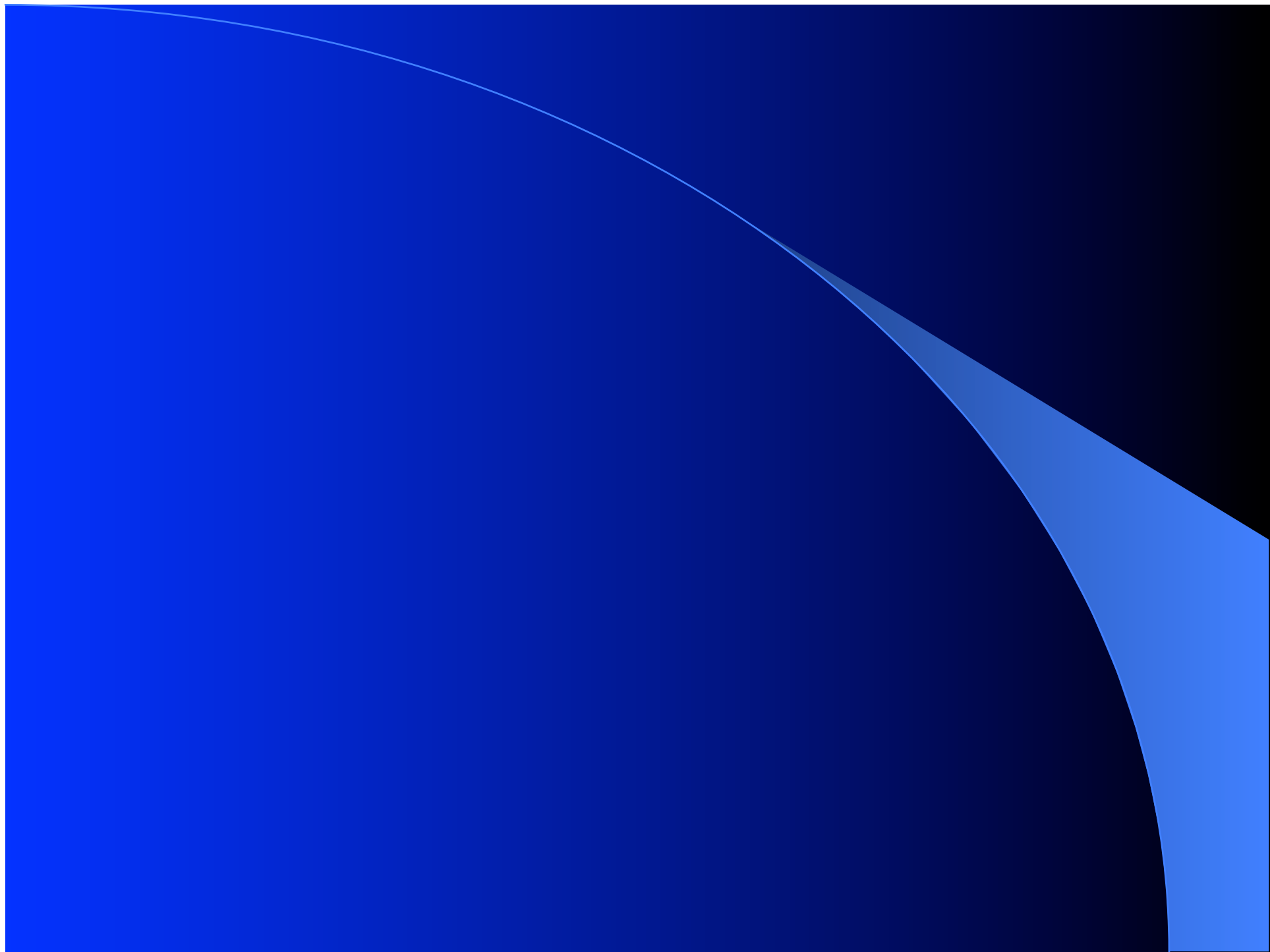
Benefits: Optimum vs No action



Effect of optimal action on benefits

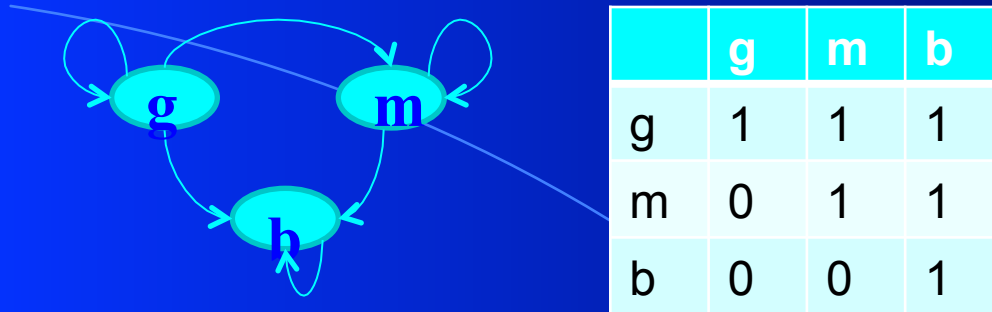
Conclusions/Future work

- The power grid system is very vulnerable if there is no warning of the solar event.
- The cascading degradation model needs to be further developed (this is a very simple model)
- Given a warning; It is important for each grid operator to communicate with others to avoid some damage
- Optimum action for a Kp9 event for the illustrative grid:
 - Washington .5, (reduction by 50%)
 - Oregon .7 (reduction by 30%)
 - California .7 (reduction by 30%)
- The model can be applied to a global power grid to identify optimal actions. Then: implementation process/fund transfer?

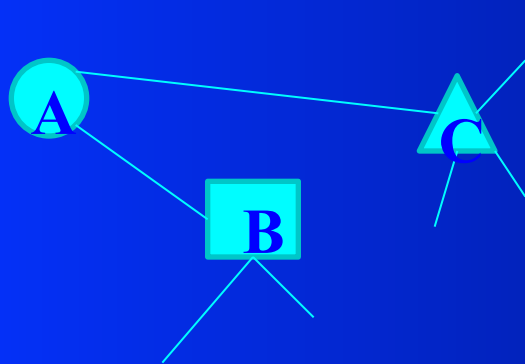


Cascading failures model

- Each node G, T, L has 3 states: good (1), medium (2) and bad (3)



- Each neighbor pair (A, C or A, B) has a transition probability



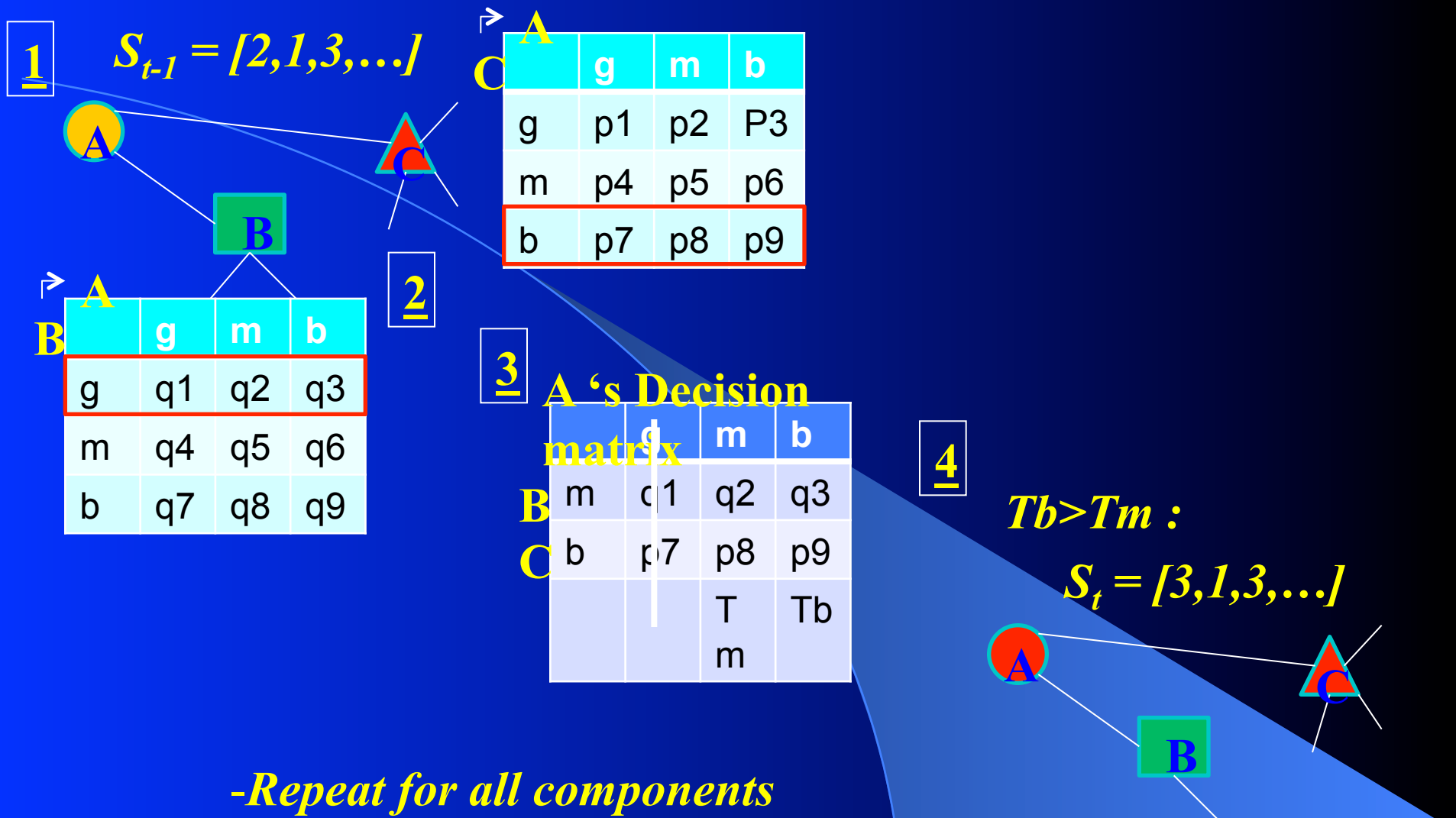
→ A

C	g	m	b
g	p	p	p
m	p	p	P
b	p	p	p

→ A

B	g	m	b
g	p	p	p
m	p	p	P
b	p	p	p

Information cascading model



Information cascading model

- Each node decides what state it will be by weighting the effect of its neighbors.



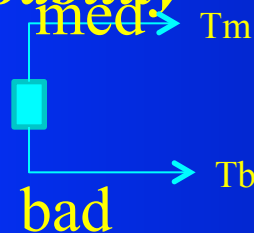
→ A

C	g	m	b
g	p1	p2	p3
m	p4	p5	p6
b	p7	p8	p9

→ A

B	g	m	b
g	q1	q2	q3
m	q4	q5	q6
b	q7	q8	q9

- At $t-1$, B was at m, C at b, A at m → state $S = [1,2,3,...]$
 - At t , A will have to make a decision based on the highest probability



A

	g	m	b
B	m	q4	q5
C	b	p7	p8
		Tm	Tb

- Repeat for all nodes:
 new $S = [2,3,3,1...]$

